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# Particulate Matter Filtration Design Considerations for Crewed Spacecraft Life Support Systems

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**Particulate matter filtration is a key component of crewed spacecraft cabin ventilation and life support system (LSS) architectures. The basic particulate matter filtration functional requirements as they relate to an exploration vehicle LSS architecture are presented. Particulate matter filtration concepts are reviewed and design considerations are discussed. A concept for a particulate matter filtration architecture suitable for exploration missions is presented. The conceptual architecture considers the results from developmental work and incorporates best practice design considerations.**

## Nomenclature

<i>BFE</i>	=	bacteria filter element
<i>EP</i>	=	electrostatic precipitator
<i>EVA</i>	=	extravehicular activity
<i>HEPA</i>	=	high efficiency particulate air
<i>HVAC</i>	=	heating, ventilation, and air conditioning
<i>ISS</i>	=	International Space Station
<i>LSS</i>	=	life support system
<i>MPPS</i>	=	most penetrating particle size
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>SBIR</i>	=	Small Business Innovative Research Program
<i>SFA</i>	=	scroll filter assembly
<i>ULPA</i>	=	ultra-low penetration air
<i>a</i>	=	particle radius
<i>A</i>	=	electrode area
<i>C<sub>c</sub></i>	=	Cunningham slip coefficient
<i>cm</i>	=	centimeter
<i>d<sub>i</sub></i>	=	inlet diameter
<i>d<sub>50</sub></i>	=	50% particle cut size
<i>D</i>	=	cyclone diameter
<i>E<sub>T</sub></i>	=	total filtration efficiency
<i>E<sub>o</sub></i>	=	electrical field strength at the point where the particle receives its equilibrium charge
<i>E<sub>p</sub></i>	=	electrical field strength at the point of particle precipitation
<i>h</i>	=	hour

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$m$	=	meter
$mg$	=	milligram
$N$	=	number of turns
$P$	=	particle penetration
$Re$	=	Reynolds number
$St$	=	Stokes number
$U$	=	jet velocity
$V_t$	=	transverse velocity
$V_i$	=	inlet velocity
$V$	=	velocity
$w$	=	migration velocity
$W$	=	jet diameter
$\mu$	=	viscosity
$\mu m$	=	micrometer
$\eta$	=	decimal efficiency
$\rho$	=	density
$\rho_p$	=	particle density
$\rho_g$	=	gas density

## I. Introduction

**P**ARTICULATE matter in various forms presents challenges to maintaining the atmospheric quality and protecting sensitive equipment in a crewed spacecraft or habitat. The particulate matter introduced into a crewed spacecraft's cabin environment typically includes fabric lint, skin fragments, hair, food debris, and paper and plastic debris.<sup>1</sup> During surface exploration missions, surface dust intrusion during extravehicular activity (EVA) activities can be expected to add to the basic particulate matter load. Compounding the challenge, in the low- and micro-gravity conditions that exist during space exploration missions, particle settling is at best insignificant. As a result, particulate matter introduced into the habitable environment remains suspended in the cabin atmosphere.<sup>2</sup> These challenges require a robust active particulate matter removal and disposal capability to maintain the suspended particulate matter load produced by basic sources below the National Aeronautics and Space Administration (NASA) standard of 3 mg/m<sup>3</sup> for the size range <100  $\mu m$ .<sup>3</sup> The surface dust <10  $\mu m$ , using lunar regolith as the basis, must be maintained below 0.3 mg/m<sup>3</sup> for episodic exposures over a 6-month period.<sup>4</sup> This covers the fine and ultrafine lunar dust particle size distributions observed in the 0.3  $\mu m$ -0.4  $\mu m$  and 1.1  $\mu m$ -1.2  $\mu m$  ranges.<sup>5</sup> The following discussion describes the role of particulate matter removal and disposal in an exploration life support system (LSS) architecture as well as provides guidance relative to filtration design, describes filter testing, and describes a conceptual particulate matter removal and disposal architecture.

## II. Particulate Matter Filtration in an Exploration Life Support System

Designing the particulate matter removal and disposal equipment for future exploration missions requires insight on the expected particulate matter load and generation sources as well as on the way particulate matter behaves. Understanding the load and sources helps determine the needed equipment size while understanding particulate matter behavior helps select technical solutions that are suitable for an exploration LSS architecture.

### A. Guidance on Particulate Matter Load and Generation Sources

In addition to the airborne particulate matter standards, the particulate matter removal and disposal equipment designers must have guidance on the expected particle size ranges and production rates for the basic and surface dust loads. Studies of particulate matter returned from crewed spacecraft have found that nearly 95% of the basic particulate matter load by mass is >500  $\mu m$  in size. Of the fraction <500  $\mu m$ , under 2% by mass is <100  $\mu m$ .<sup>6</sup> This fraction <100  $\mu m$  must be maintained below 3 mg/m<sup>3</sup> to ensure crew health. The estimated basic load that must be controlled below this limit ranges between 0.6 mg/person-minute and 1.6 mg/person-minute.<sup>7</sup>

Early deep space exploration mission development has estimated that 227 grams of surface dust/EVA crewmember may be introduced into the habitable environment. It is estimated that the fraction below 10  $\mu m$  would become suspended in the cabin atmosphere. This fraction is estimated to be seven percent by mass which establishes a suspended surface dust load of ~15.9 grams/EVA crewmember.<sup>8</sup> The dust intrusion rate is approximately seven times the daily basic particulate matter load attributed to a single crewmember per day. This is a significant particulate matter load challenge. Analysis has indicated that dust intrusion barrier effectiveness >99% is necessary to avoid needing a very

large, high flow particulate matter removal and disposal system for surface exploration missions.<sup>9</sup> Life support system development has been focusing most recently on transit between Earth and deep space exploration destinations. Therefore, the surface dust component has not been a near-term driving requirement. However, surface dust intrusion will certainly have to be a major consideration to future surface exploration pressurized habitats and vehicles.

### B. Particulate Matter Filtration in the Life Support System Architecture

Life support system architectures under evaluation have included a particulate matter removal and disposal approach that consists of multiple filter stages—a debris screening stage, an inertial mid-size particulate removal stage, an indexing or scroll media stage, and a high efficiency media stage.<sup>10, 11</sup> This concept can be applied to both crew transit and surface exploration applications. Recent work has been focusing on the second and third stages.<sup>12, 13</sup>

## III. Particulate Matter Filtration Design Considerations

Incorporating the particulate matter removal and disposal components into a LSS architecture requires careful consideration for various technical aspects associated with filtration and filter design. Considerations relating to particulate matter capturing mechanisms, capturing efficiency, and combining filtration and with adsorbent beds are presented by the following discussion.

### A. Particulate Matter Capturing Mechanisms

Technologies for the control and removal of airborne particulate matter are well established. The technologies most typically used are mechanical filtration, inertial separation, and electrostatic precipitation. The choice of technology best suited for the application depends on the particulate matter environment and the cleanliness requirements. A discussion of some of the key design and operational aspects of these technologies follows.

Fibrous filter media which are used ubiquitously in residential, commercial and industrial application offers highly effective particulate matter capture over a broad size range. The process of capturing particles on the fibers of the filter media depends on the properties and conditions of the incoming flow, the flow characteristics through the internal microstructure of the filter, and the particle's transport (aerosol) properties. The tortuous pathways created by the interconnected interstices between the fibers significantly enhances the residence time of particles inside the media. These factors lead to three basic flow-related capturing mechanisms known as the inertial impaction, interception, and diffusion mechanisms. It is instructive to illustrate the different capturing mechanisms as they are not well known outside the media filtration field. Fig. 1 provides a visual depiction of the particle dynamics and particle-fiber interactions involved in the different capture mechanisms. The fates of different diameter particles along the isolated streamlines are illustrated. Very small diameter particles, as shown in the top streamline, are most susceptible to Brownian motion and are intermittently and incrementally knocked off the stream path by molecular collisions. Due to the randomness of the diffusional collisions the particles have a chance to approach a fiber surface and become trapped. The effect of the interception mechanism is illustrated in the next (from the top) streamline as the particle comes within one radius of the surface of the fiber. In this case the particle has sufficient contact time with the fiber surface to also become trapped. The mechanism involved in the straining capturing mode, found more typically in surface filtration, is shown depicted on the third streamline from the top. It is recognized that this mechanism only plays a role for very large particles that are typically collected on the front face of the filter media. Lastly, inertial impaction is the dominant capturing mechanism for the large diameter particle, as shown by the particle following the bottom streamline. The large inertia causes the particle to deviate from the streamline path when it encounters sufficient flow curvature. If sufficiently massive, the particle directly impacts onto the fiber surface and adheres to it. Adhesion forces (Van der Waals, electrostatics, and capillary) between small particles ( $<10\ \mu\text{m}$ ) and the fiber surfaces as a result of the different capturing mechanisms ensures collected particles stay on the fibers.

In inertial separation devices, inertial separation is produced when particles larger than a certain specified cut size are removed from the main flow and driven towards a collection surface or collection device. Cyclone

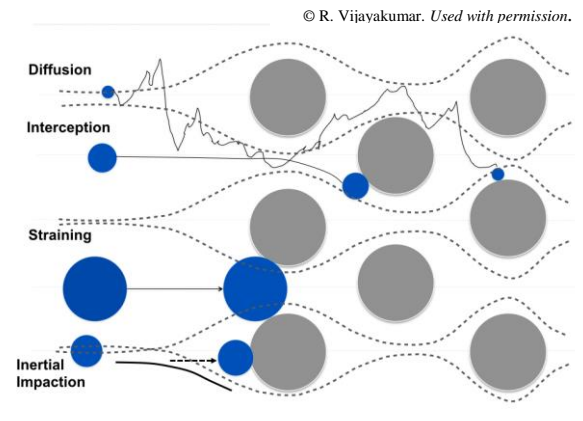


Figure 1. Particle capture mechanisms.

separators, impactors, and impingement plates are examples. These separators offer large holding capacity of collected particulate matter, but typically generate large pressure drops. They are also challenging to integrate to standard size ventilation ducts. In cyclone separators, particulate matter in the flow is forced towards the cyclone wall due to the centrifugal force produced by the downward spiral flow in the cyclone. The centrifugal force scales with the mass of a particle and therefore the largest or heaviest particles are collected on the walls or in the collection cup, while the lightest and smallest particles evade the walls and are directed to the cyclone outlet. A key theoretical factor is the time it takes a particle of a certain mass (diameter and density) to drift transversely from the inside edge of the spiral stream tube to the outside edge where it meets the wall. The transverse velocity is given by Eq. 1.

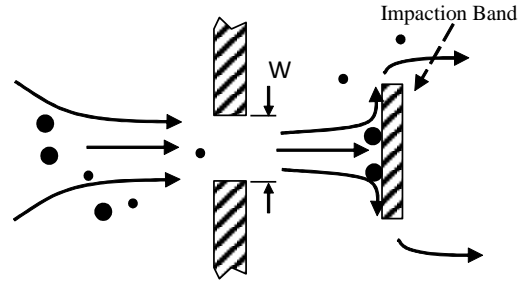
$$V_t = \frac{(\rho_p - \rho_g)d_p^2 V_i^2}{9\mu D} \quad (1)$$

In Eq. 1  $\rho$  is density,  $d_p$  is the particle diameter,  $V_i$  is the inlet velocity,  $\mu$  is the gas viscosity,  $D$  is the cyclone diameter, and subscripts  $p$  and  $g$  pertain to the particle and gas properties respectively. Note that large differences in densities between the particle and the gas, high inlet velocities, and a small cyclone body diameter lead to higher transverse velocities and the possibility of removing smaller diameter particles.

A similar dynamic occurs with inertial impactors. In this case the possibility of a particle becoming trapped on the collection surface is given by the particle's Stokes number as defined by Eq. 2.

$$St = \frac{\rho_p d_p^2 C_c U}{9\mu W} \quad (2)$$

Here  $W$  is the diameter of the jet and  $U$  is the jet velocity. The parameter,  $C_c$ , is the Cunningham slip coefficient. Unlike the transverse velocity above, the Stokes number is dimensionless but it highlights the fact that virtually the same variables are responsible for particle collection. Particles with large Stokes numbers (e.g. large or dense particles, particles in high speed jets, or small aperture impactors) tend to get trapped on the collection surface, while particles with small Stokes numbers circumvent it. The graphic in Fig. 2 depicts this behavior for different size particles as they pass through an impactor aperture and approach the collection band. The high turning angle encountered near the bluff impactation surface, causes relatively large particles (large Stokes number) to impact on the surface while the smaller particles, which are well entrained in the flow, avoid it and continue downstream with the flow.



**Figure 2. Particle capture by inertial impact.**

Another effective removal method is electrostatic capturing or precipitation. Particles are introduced into a zone in the flow filled with ions (of both polarities) where they quickly attain a limiting surface charge. The electrostatic force on the particles is proportional to the charge on the particle and the applied electric field,  $F=qE_0$ , which is balanced by the aerodynamic drag force as it transits through the ion zone. The time the particle stays in the electric field determines whether it will be collected and is dependent on the electric field, particle diameter, and distance to the collector among the key design and operational parameters.

## B. Particulate Matter Capturing Efficiency

Considerations for optimizing removal efficiencies for particulate matter removal techniques are presented by the following discussion for media filters, cyclonic separations, and electrostatic separations.

### 1. Media Filter Efficiency

The efficiency of media filters is tied to the influence of the various competing particle capturing mechanisms discussed above. Single Fiber Theory forms a basis for determining the bulk efficiency of the media. The theory considers the idealized analysis of the flow around an isolated uniform diameter fiber. The utility of the theory is in showing the dependence of different particle and flow properties on filter efficiency. According to the theory, the overall single fiber efficiency,  $E_T$ , is found from the product of the compliment of all the individual single fiber efficiencies (i.e. inertial impactation,  $I$ , diffusion,  $D$ , interception,  $R$ , diffusion and interception combined,  $DR$ , and efficiency due to gravity,  $G$ ) and given by Eq. 3.

$$E_T = 1 - (1 - E_I)(1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_G) \quad (3)$$

According to the theory of particle removal by of a high efficiency particulate air (HEPA) filter developed in the 1980s, the capture efficiency due to the different mechanisms discussed above varies as a function of particle diameter.<sup>14, 15</sup> This is shown in Fig. 3. Superimposed are plots showing the trends found from single fiber theory, and showing the relative importance of the different particle capture mechanisms in contributing to the shape of the efficiency curve. The combination of the competing capture mechanisms results in the pronounced minimum efficiency shown in Fig. 3, which is unique to fibrous filters. This is also referred to as the most penetrating particle size (MPPS). Particulate matter larger and smaller than the MPPS are removed more efficiently, approaching 100% efficiency, from the flow. For HEPA-rated filters, the particulate matter of interest is in the sub-micron size range. The capturing mechanism in this size range is diffusion dominated. The low flow velocities through HEPA-rated filters further aid the effect of diffusion capture. Hence these filters are often considered to be diffusion dominated. A small fractional difference in efficiency can provide categorically different grades in filter media. For example, HEPA-rated efficiency is defined as 99.97% for the MPPS while ultra-low penetration air (ULPA)-rated efficiency is 99.999%.

In HEPA-rated filters, the flow velocities are usually quite low. At these velocities, the resistance to air flow is in the D'Arcy regime for flow through porous beds, as illustrated by Fig. 4, and varies linearly with air flow rate. At higher flow rates common in pre-filters and general ventilation filters, the velocities are higher and the relationship becomes somewhat non-linear.

Small changes in flow velocities through the media result in large changes in particle penetration through the filter. Particle penetration,  $P$ , is defined simply as the number of particles crossing the filter divided by the number of particles incident on the filter and is related to overall efficiency,  $E_T$ , as  $P = 1 - E_T$ .<sup>16</sup> As a rule of thumb, reducing the velocity by half not only reduces the pressure drop by half but also decreases particle penetration through the filter media by nearly an order of magnitude. This is illustrated in Fig. 5 where decreasing the velocity by three-fourths reduces the particle penetration over three orders of magnitude with a corresponding efficiency increase from 99.998% to 99.99998%. In other words, a simple HEPA-rated filter will perform as an ULPA-rated or better filter by simply lowering the flow velocity through the media.

It is worth noting that while the performance of a filter is determined by the velocity of flow through the media, the filter's design can handle much larger flow rates than the media itself. Filter designs balance the quantity of pleated media in a filter and the filter media performance so that the filter will meet the desired specifications. For example, one may use larger numbers of pleats of a lower efficiency grade of media to achieve a higher efficiency filter or vice versa. Hence, for most indoor air quality applications where low energy consumption is desirable, particularly for space habitats, it is good practice to specify filters with the lowest media velocities that yield the highest performance at the lowest energy burden.

In general, HEPA- and ULPA-rated filters are used as a finishing filters and are often positioned at the fresh air outlet of

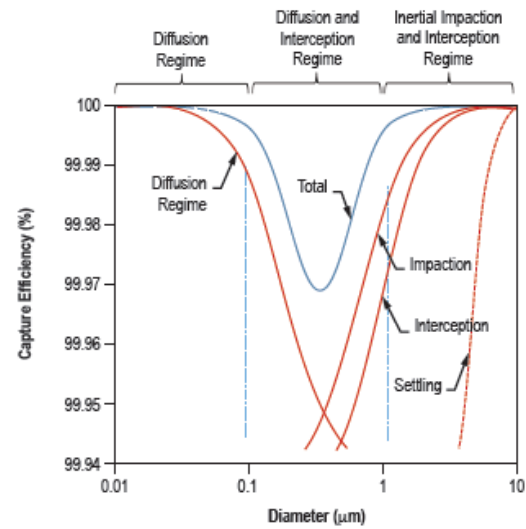


Figure 3. HEPA filter capture efficiency.

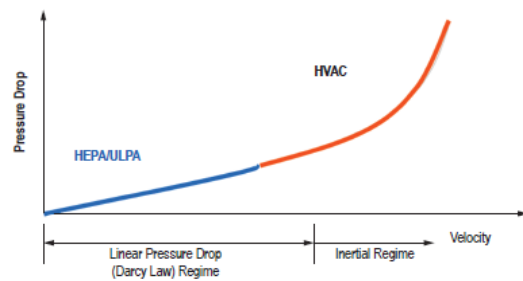


Figure 4. Flow velocity has influences on pressure drop. ©R. Vijayakumar. Used with permission.

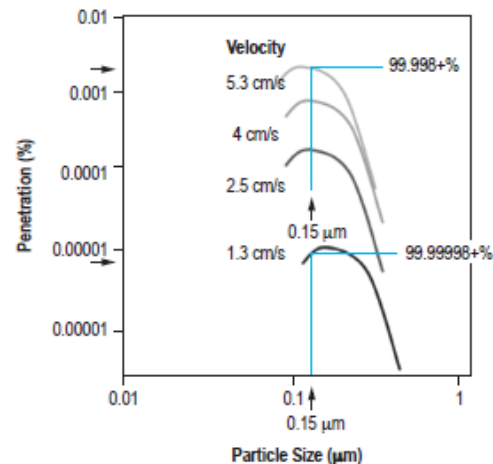


Figure 5. Filter efficiency depends on flow velocity. ©R. Vijayakumar. Used with permission.

a clean space. The high efficiency of these filters result in rapid clogging of the filter in dusty atmospheres. Hence it is rare to use HEPA- or ULPA-rated filters without one or more stages of pre-filtration. Modification of the filtration media to achieve so-called smart media can allow for regenerating the media. Such media use advances in polymer coatings to produce a response of the media to break up or dislodge particles during a regeneration cycle.

## 2. Cyclonic Separation Efficiency

Efficiency in cyclonic separation is obtained by optimizing the geometric design. The efficiency of the cyclone separator is determined by the 50% particle cut size given by Eq. 4.

$$d_{50} = \left[ \frac{9\mu d_i}{2\pi N V_i (\rho_p - \rho_g)} \right]^{1/2} \quad (4)$$

In other words, Eq. 4 describes the particle cut size is the diameter at which particles are collected with 50% efficiency. The variable  $N$  refers to the number of turns in the spiral flow produced inside the cyclone and is an important design variable that is directly dependent on the cyclone geometry. The key design control parameters for cyclone separators are the number of turns ( $N$ ), inlet diameter ( $d_i$ ), and velocity ( $V_i$ ). Similarly the  $d_{50}$  for the inertial impactor is given by Eq. 5.

$$d_{50} = \sqrt{\frac{9W^2 Stk_{50}}{C_c \rho_p Re}} \quad (5)$$

In Eq. 5,  $Re$  is the particle Reynolds number,  $d_p U/\mu$ . The collection efficiency curve is quite steep and the rise is centered at the  $d_{50}$  diameter. The parameter,  $Stk_{50}$ , is referred to as the critical Stokes number and its value is specifically set in the design of the impactor. Typically for a rectangular orifice opening a Stokes number value of 0.59 is prescribed while a Stokes number value of 0.24 is recommended for a round jet.<sup>17</sup> The main design factor is the jet width and velocity.

## 3. Electrostatic Separation Efficiency

Electrostatic precipitation (EP) is often used for emission control of fine dust in a host of industrial processes. Electrostatic precipitation is typically effective for capturing small particles. The collection efficiency is governed by the electrostatic force and hydrodynamic transport of the particle. An ion generation source, typically a corona wire, is required to charge the transporting particles in an applied electric field formed by the ion source and an electrode surface. The collection efficiency is characterized by the Deutsch equation as shown by Eq. 6.<sup>18</sup>

$$\eta = 1 - e^{-w(A/V)} \quad (6)$$

In this relationship  $\eta$  is the collection decimal efficiency,  $w$  is the migration velocity in cm/s,  $A$  is the area of the collecting electrodes in m<sup>2</sup>, and  $V$  is the process gas flow in m<sup>3</sup>/s. The performance of EPs is dependent on the migration velocity,  $w$ , which is proportional to the electrical field strength and the particle's diameter as shown by Eq. 7.<sup>19</sup>

$$w = \frac{aE_o E_p}{6\pi\mu} \quad (7)$$

In Eq. 7  $a$  is the particle radius in cm,  $E_o$  is the electrical field strength at the point where the particle received its equilibrium charge in statvolts/cm,  $E_p$  is the electrical field strength at the point of precipitation in statvolts/cm, and  $\mu$  is the gas viscosity in poise.

Despite the effectiveness of EP, the system is quite sensitive to secondary factors. The electrode is usually negatively charged and grounded for large EPs in order to maintain a large voltage potential without arcing. However this results in ozone production which must be avoided in the spacecraft cabin. Smaller EPs such as cigarette smoke cleaners use a positively charged electrode to minimize ozone production but increase the chances of arcing. Also there is some variability in collection efficiency that has to do with the electrical resistivity of the particles and local charge dynamics which cannot be fully accounted for by the EP design.

Conductive particles lose their charge when they reach the electrode, and therefore EP is applicable only to dielectric particles. For dielectric particles there is a range of electrical resistivity. Highly resistive particles are more difficult to charge and tend to weaken the field and reduce the effectiveness of precipitation. Whereas low resistivity particles are easier to charge but tend to lose or reduce their charge when they reach the electrode making it difficult to stay attached to the electrode. Therefore particles of moderate resistivity tend to perform best with EPs. In addition, the possibility of electrical breakdown in the dust layer may also compromise performance.

Rapping (shaking or tapping) of the collection surface is often used in an industrial system to achieve regeneration. A collection bin below the plates captures the dislodged particles. Alternatively, smaller residential systems are taken off line and the collection surfaces are placed in a cleaning bath for regeneration. Both regeneration schemes require planning for additional infrastructure and crew involvement in a future LSS architecture.

An interesting application of EP is an electrically-enhanced media filter. In this EP-derived application, the particulate matter loading capacity and resulting efficiency of filtration media is enhanced by manipulating and electrostatic charge on the filtration media.<sup>20</sup> Incorporating an electrostatic component to a media filtration application may be advantageous for future exploration missions.

### C. Particulate Matter Filtration in Combination with Packed Adsorbent Beds

Packed beds of granular or pelletized porous adsorbent media are typically used for the removal of gaseous and molecular contaminants. Beds of substantial depths may also provide an assist to media filters for removing particulate matter <0.1  $\mu\text{m}$  in size. Studies on particulate matter removal by packed beds have found that, similarly to HEPA media filters, the 0.3- $\mu\text{m}$  size is the MPPS.<sup>21</sup> These studies, however, found that packed bed efficiencies for removing 0.3- $\mu\text{m}$  size particles, the HEPA media filtration MPPS, are an order of magnitude lower than for particulate matter <0.1- $\mu\text{m}$  and >1.0- $\mu\text{m}$  in size.<sup>22</sup> Therefore, while deep packed beds have been shown experimentally to remove ultrafine and coarse particulate matter, they are not suitable by themselves for providing effective particle removal. Using adsorbent beds for particle removal usually reduces the effectiveness and life of the bed for gaseous and molecular contaminants due to loading of the pores in the adsorbent media with particulate matter. For these reasons, it is common industrial practice to rely on adsorbent beds only for gaseous filtration. It is also common practice to install particle filters upstream of the adsorber beds, both to filter particles and to prevent the adsorber bed from becoming loaded with particulate matter.

## IV. Particulate Matter Removal Technology Comparison

Table 1 summarizes the previous discussions on the various filtration and separation techniques. Each particulate removal techniques has benefits and disadvantages, highlighted by Table 1, that need to be carefully considered in the planning of spacecraft architectures suitable for long duration exploration missions. Also, there are some techniques that may complement each other that when used in combination as a multi-stage configuration could offer more extensive capability and performance than employing technologies individually.

**Table 1. A comparison of particulate matter removal techniques.**

TECHNOLOGY	BENEFITS	DISADVANTAGES
Media Filtration	<ul style="list-style-type: none"> <li>•Low to very high efficiency</li> <li>•Very broad size range from nanometers to 10's of microns</li> </ul>	<ul style="list-style-type: none"> <li>•Challenges under high dust loading conditions requiring pre-filtration and filter logistics management to provide good capacity</li> <li>•Regeneration possible but complicated</li> </ul>
Cyclone separation	<ul style="list-style-type: none"> <li>•Size range limited to particles larger than a few microns</li> <li>•Large holding capacity</li> <li>•Can handle large particle concentrations</li> <li>•Regenerable</li> </ul>	<ul style="list-style-type: none"> <li>•Large pressure drop</li> <li>•Requires flow cessation for regeneration</li> <li>•Emptying the particulate collection receiver</li> </ul>
Inertial Impaction	<ul style="list-style-type: none"> <li>•Large holding capacity</li> <li>•Can handle large particle concentrations</li> <li>•Particulate capture in scroll reduces handling by crew during maintenance</li> <li>•Regenerable</li> </ul>	<ul style="list-style-type: none"> <li>•Large pressure drop for small particle size</li> <li>•Requires flow cessation for regeneration</li> <li>•Scroll mechanism introduces complexity</li> </ul>
Electrostatic Precipitation	<ul style="list-style-type: none"> <li>•Effective for capturing small particles</li> <li>•Regenerable</li> </ul>	<ul style="list-style-type: none"> <li>•Complexity</li> <li>•Power consumption</li> <li>•Ozone generation</li> </ul>
Hybrid media and packed bed filtration	<ul style="list-style-type: none"> <li>•Primarily for gaseous contaminant removal</li> <li>•Can offer some particle pre-filtration</li> </ul>	<ul style="list-style-type: none"> <li>•Complexity and compatibility</li> <li>•Requires particulate matter pre-filters</li> </ul>

## V. A Particulate Matter Filtration Concept for Exploration Missions

Advanced particulate matter filtration concepts take advantage of the best features of particulate matter removal techniques toward providing the reliability, durability and minimal maintenance needed for future crewed space exploration missions. To meet these objectives the filtration system will need to comply with specific requirements tailored to the environment and operational constraint of the missions. Systems will have to be prototyped and tested in relevant environments to demonstrate their compatibility and effectiveness with these environments.

### A. Particulate Matter Filtration Technology Development

Developmental work has been conducted toward a particulate matter filtration concept that addresses exploration mission functional requirements and constraints. Filtration needs and technical options have been surveyed for the application.<sup>23, 24</sup> As a result of these survey efforts, key areas for development to address the needs include cyclonic cleaners, regenerative media, indexing media, electrospray, and advanced media. The following briefly summarizes these developmental areas.

#### 1. Cyclonic Cleaners

The performance of cyclone separators were investigated under a range of pressures from ambient to 200 Pa.<sup>25</sup> The reduced pressure environments were relevant to lunar landers and habitats under the Constellation program. Premium efficiency cyclones were tested and found to perform well. Their potential use as pre-filters to remove particles greater than three microns with a pressure drop <250 Pa was verified under reduced pressure.

#### 2. Regeneration Schemes using Media and Cyclonic Separation

A combination of surface pre-filtration and inertial/cyclonic particulate separation was studied as a regeneration scheme under microgravity.<sup>13</sup> Central to the regeneration scheme was a flow partition that acted as three-way valve to redirect the flow through the cyclone separator as the pre-filter element was cleaned using back-pulses of air. The dislodged dust layer was also suctioned through the by-pass line and captured in the cyclone separator collection cup. The results were met with some success but the complexity and additional system infrastructure required will need to be addressed.

#### 3. Indexing Media Filter Systems

An indexing media filter, initially designed under an Innovative Partnership Program (IPP) project between NASA and Aerfil, LLC, has been prototyped and performance tested.<sup>12, 26</sup> The filtration system consists of three stages—an inertial impactor stage, an indexing media stage, and a high-efficiency filter stage. These stages are packaged in a stacked modular cartridge configuration. Each stage targets a specific range of particle sizes that optimize the filtration and regeneration performance of the system. This multi-stage configuration should result in long-duration operation, high loading capacity, and minimal servicing and maintenance.

#### 4. Electrospray

Electrospray particle capture technology is a variant of EP which employs a mist of highly charged micro-droplets generated by electrospray ionization to charge incoming particles.<sup>27</sup> As particles come in contact with the highly charged droplets they either adhere to them or acquire their charge through charge transfer. Charged electrode plates are used to capture the charge particles. They offer the advantage of no ozone production, compactness, and low power operation.

#### 5. Advanced Filtration Media

A variety of advanced filtration media based on membranes and carbon nanotubes have been under development by SBIR projects. Details on performance as these media become more mature are of interest for adaptation to exploration mission particulate matter filtration architectures.

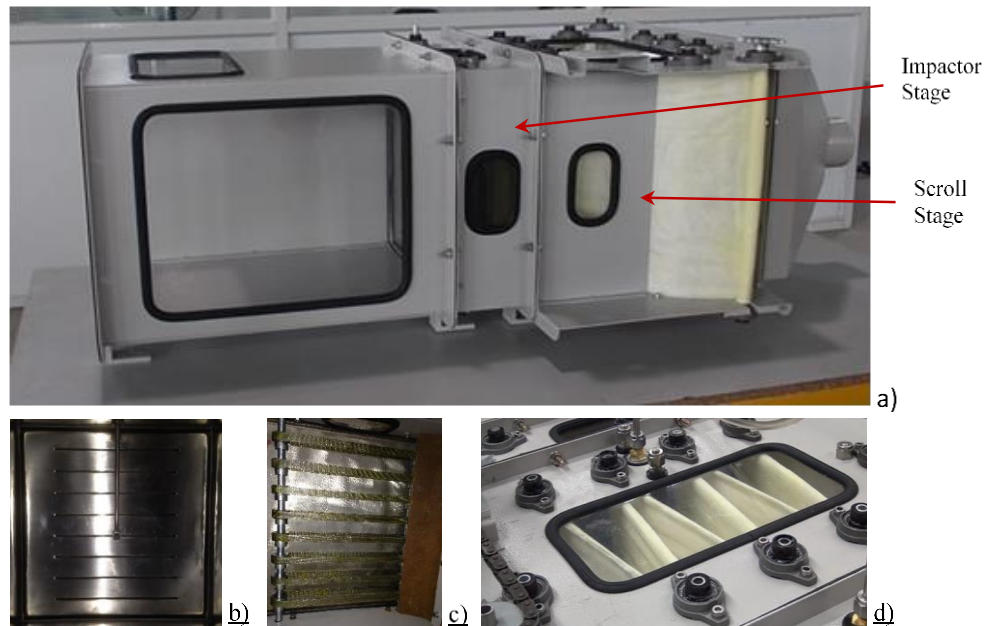
### B. An Indexing Media Filter System for Exploration Missions

Results from the variety of particulate matter filtration developmental areas provide insight for a proposed particulate matter filtration concept suitable for exploration missions. Of the developments described above the Indexing Media Filter System offers the most flexibility and adaptability to address the varied challenges for crewed exploration missions. The filter system known as the Scroll Filter Assembly (SFA), consists of three stages as described above. An additional pre-filtration mesh screen stage can also be incorporated based on requirements. Figure 6 shows pictures of the hardware and some of the internal components. The inertial impactor uses an orifice plate and endless belts for the collection surfaces which are shown respectively in Figs. 6b and 6c. The collection belts are regenerated when they become heavily loaded by rotating them mechanically on a periodic basis or as needed to scrape off the particles. In the scroll stage of the SFA, reserve filter media, sufficient for several media change-outs, is provided in a supply spool. Internal spindles supported on bearings help reshape the filter media with pleats inside the stage as shown by



Fig. 6d. The deployment of fresh media may be activated autonomously by a differential pressure control set point corresponding to a loaded media state, thus the system possesses self-maintenance capability.

Each stage of the SFA targets a specific range of particle sizes that optimize the filtration and regeneration performance of the system. It incorporates the advantages of media filtration with inertial separation and impaction. The modular design also provides the flexibility to add more stages of filters for performance optimization, and to meet design and operational requirements of any space or sealed environment mission. Future enhancements or performance adjustments in either the inertial or media filtration stages are also facilitated by the modular design. Alternate stages can be considered and may include inertial technologies such as cyclonic flows, electrostatic precipitation, or new higher performing media such as those developed under projects sponsored by the Small Business Innovative Research (SBIR) Program.



**Figure 6. The Scroll Filter Assembly.** *a) Scroll Filter System with the inlet and outlet contraction attached for testing) (b) impactor orifice plate, (c) impactor filter collection belts, (d) scroll stage showing media threaded on the spindle pleat system*

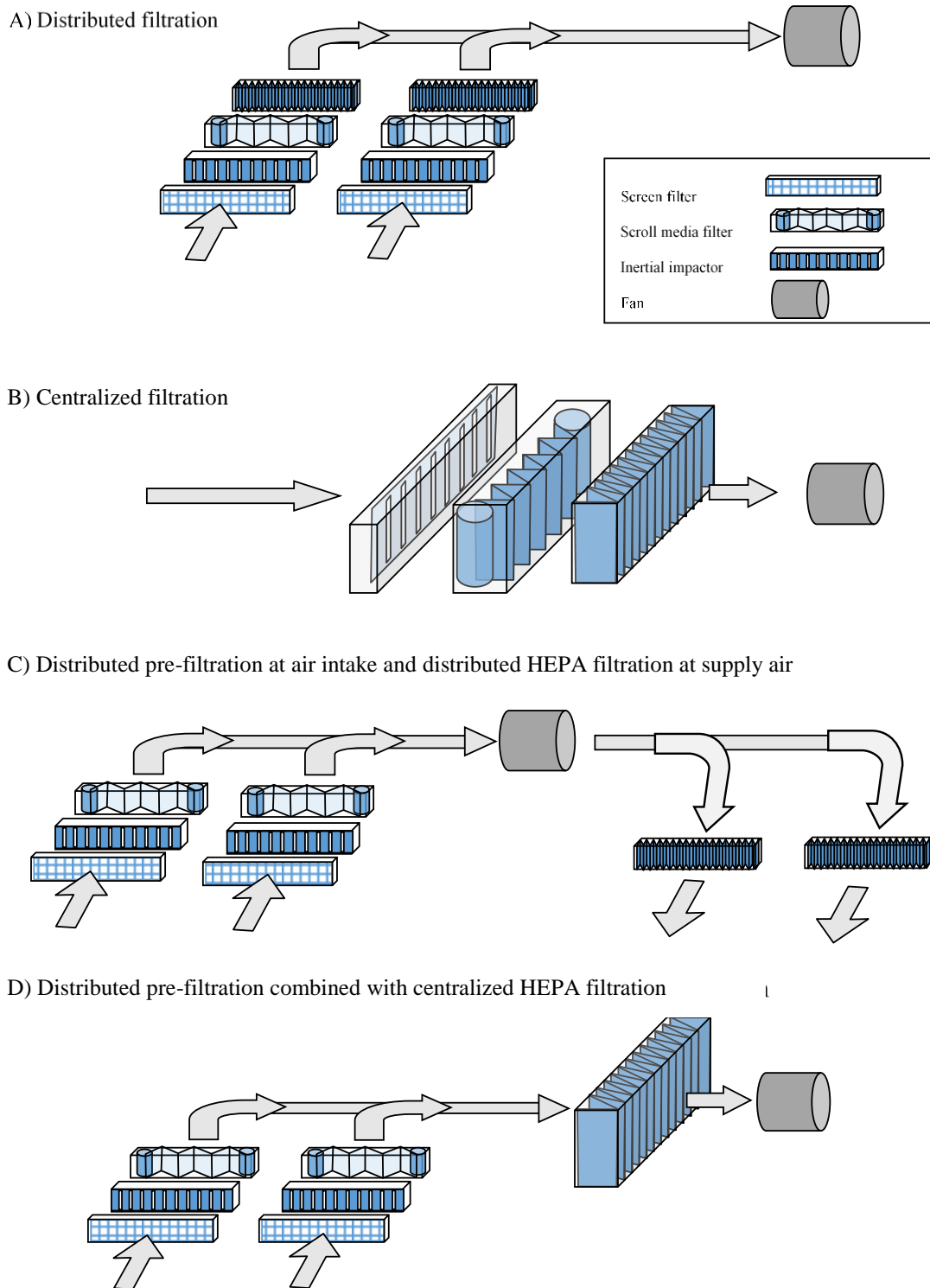
### C. Particulate Matter Filtration Component Integration with the Cabin Ventilation System

The SFA may serve as the basis for developing the particulate matter removal and disposal aspect of future spacecraft LSS architectures. The multi-stage and modular design offers many advantages, as described above, that provide options for tailoring filtration performance. Additional flexibility in performance can be obtained by separating the functions and stages of the filter system between the distributed and centralized sections of the cabin ventilation system. Four possible configurations are presented in Fig. 7.

The distributed multistage configuration appears in configuration A. Here all the filtration takes place at each of the return air filter registers. Distributed air handling offers a means of expanding the cabin ventilation throughout the cabin and minimize dead circulation zones. This approach is incorporated in most of the International Space Station (ISS) modules that comprise the U.S. Segment.

Centralized filtration is shown in configuration B. This approach is employed by the ISS's *Columbus* laboratory module. Typically large volume filter elements are required to handle the large flow rates encountered in the centralized ventilation zone. Centralized ventilation results in a smaller number of components; however, the size of the components can introduce mass and volume challenges, particularly with respect to spare component logistics. Also centralized ventilation flows produce localized flows that do not effectively cover the whole cabin.

Configuration C consists of distributed pre-filtration at the air return registers to the ventilation system and HEPA-rated filtration at the air supply vents to the cabin. Positioning the HEPA media filter at air supplies ensures the cleanest air enters the cabin, free from any particles that could be generated by the trace contaminant or CO<sub>2</sub> removal adsorbent media or other sources within components that purify the cabin atmosphere.



**Figure 7. Particulate matter filtration concepts for exploration vehicles.**

Lastly, configuration D consists of distributed pre-filtration and centralized HEPA-rated media filtration. The inertial impaction and scroll media stages are best utilized for the distributed pre-filtration stage. The high efficiency media is expected to provide long operational life, not requiring any servicing, and therefore can be placed in a less accessible location. In this configuration all the pre-filtration stages are positioned at the return air registers which allows them to be more easily serviced and inspected, while the HEPA-rated media filter will reside further inside the ventilation duct downstream of where the distributed ventilation lines converge. There will be small reduction in payload because fewer HEPA-rated media elements will be required. This last configuration seems to offer the smallest payload mass and volume penalty while offering flexibility to accommodate a range of ventilation system designs.

Testing the candidate filtration system concepts will provide vital performance and component service life data. Demonstrations of deep space technologies are expected to be facilitated aboard the ISS. The ISS provides a highly relevant environment for long duration testing in microgravity. Science payloads and demonstration hardware are typically operated on a multitude of available rack platforms. However, direct integration of the filter concept to one of the filter subsystems aboard the ISS would provide the best test and challenge for the demonstration unit, provided it does not interfere with critical LSS functions. This can be accommodated in one of the modules on the ISS that uses a distributed ventilation architecture with Bacterial Filter Elements (BFE) at the return air registers. The BFE is a low profile HEPA-rated media filter element, approximately 70 cm × 10 cm × 10 cm deep, which is designed for a volumetric flow rate in the range of 85 m<sup>3</sup>/h to 127 m<sup>3</sup>/h depending on the location. Careful consideration must be given to the interfaces and seals that would be needed to replace one of the BFE's or other existing filter elements with the stages of the SFA.

## VI. Summary and Conclusions

Particulate matter removal is a key functional component within a crewed spacecraft vehicle's LSS. The basic particulate matter filtration functional requirements as they relate to the general cabin and surface exploration dust loads for deep space exploration missions were presented and discussed. Various particulate matter removal and disposal techniques suitable for addressing the particulate matter removal challenge were discussed relative to their effectiveness. Each technique has specific considerations for design relating to particulate matter size and the flow velocities necessary to adequately handle the particulate matter load aboard a crewed spacecraft. Achieving a high overall particulate matter removal efficiency while minimizing size and power, and maintenance demands are objectives for a conceptual multi-stage particulate matter removal assembly. The conceptual assembly offers architectural flexibility whereby components can be configured in distributed and centralized positions within a crewed spacecraft cabin ventilation system.

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